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A literature survey of the problem of aircraft spins

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THESIS

A LITERATURE SURVEY OF THE PROBLEM OF AIRCRAFT SPINS

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A Literature Survey of the Problem of Aircraft Spins

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ABSTRACT

The prediction of aircraft spin characteristics has defied complete scientific analysis. There are, however, a number of research techniques which have been utilized in attempts to understand the mechanism of spin. This paper presents a survey of the literature dealing with spin research and its application to a wide variety of aircraft designs over the period 1916 to 1971.

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The definitions of the symbols used throughout are as follows:

C_F applied force coefficient, $F/1/2\rho V_R{}^2S$

C_X longitudinal-force coefficient, $F_X/1/2\rho V_R{}^2S$

C_Y side-force coefficient, $F_Y/1/2\rho V_R{}^2S$

C_Z normal-force coefficient, $F_Z/1/2\rho V_R{}^2S$

C_l rolling-moment coefficient, $M_X/1/2\rho V_R{}^2Sb$

C_m pitching-moment coefficient, $M_Y/1/2\rho V_R{}^2S\bar{c}$

$C_{m,b}$ pitching-moment coefficient (subscript b denotes that pitching moment was nondimensionalized by b rather than by $\bar{c}$), $M_Y/1/2\rho V_R{}^2Sb$

C_n yawing-moment coefficient, $M_Z/1/2\rho V_R{}^2Sb$

T thrust, lb

F applied force, lb

F_X longitudinal force acting along X body axis, lb

F_Y side force acting along Y body axis, lb

F_Z normal force acting along Z body axis, lb

M_X rolling moment acting about X body axis, ft-lb

M_Y pitching moment acting about Y body axis, ft-lb

M_Z yawing moment acting about Z body axis, ft-lb

W weight, lb

$F_{X,roc}$	rocket force parallel to X body axis, lb
$F_{Y,roc}$	rocket force parallel to Y body axis, lb
$F_{Z,roc}$	rocket force parallel to Z body axis, lb
S	wing surface area, sq ft
X,Y,Z	longitudinal, lateral, and vertical body axes of airplane, respectively
b	wing span, ft
l	reference length, ft
ρ	air density, slugs/cu ft
V	vertical component of velocity of airplane center of gravity (rate of descent), fps
V_R	resultant linear velocity, fps
u,v,w	components of velocity V along X,Y,Z body axes, fps
Ω	resultant angular velocity, rps
p,q,r	components of angular velocity about X,Y,Z body axes respectively, radians/sec
ω_{eng}	engine rotational rate, radians/sec
μ	airplane relative-density coefficient, $m/\rho Sb$
m	mass of airplane, $\frac{\text{weight}}{g}$, slugs
$\bar{c}$	mean aerodynamic chord, ft
x,y,z	linear distances along three axes measured from the earth-fixed reference axis, ft
I_X, I_Y, I_Z	moments of inertia about X,Y,Z body axes, respectively, slug-sq-ft
$I_{X,eng}$	polar moment of inertia of engine, slug-sq-ft
I_{XZ}	product of inertia about X and Z body axes, slug-sq-ft

$\frac{I_X - I_Y}{mb^2}$ inertia yawing-moment parameter

$\frac{I_Y - I_Z}{mb^2}$ inertia rolling-moment parameter

$\frac{I_Z - I_X}{mb^2}$ inertia pitching-moment parameter

g acceleration due to gravity, ft/sec-sq

θ_E total angular movement of X body axis from horizontal plane, deg

ϕ_E total angular movement of Y body axis from horizontal plane measured in YZ body plane, deg

k_X, k_Y, k_Z radii of gyration about X,Y,Z body axes, respectively, ft

ϕ angle between Y body axis and horizontal measured in vertical plane, deg

α angle of attack, angle between relative wind V_R projected into the YZ plane of symmetry and the X body axis, deg

β angle of sideslip, angle between relative wind V_R and projection of relative wind on XZ plane, deg

ψ angle of inclination of a yaw vane with respect to X body axis, deg

ψ_E horizontal component of total angular deflection of X body axis from reference position in horizontal plane, deg

$$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{Y_{\dot\beta}} = \frac{\partial C_Y}{\partial (\frac{\dot\beta b}{2V_R})}$$

$$C_{Y_p} = \frac{\partial C_Y}{\partial (\frac{pb}{2V_R})}$$

$$C_{Y_r} = \frac{\partial C_Y}{\partial (\frac{rb}{2V_R})}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{l_{\dot\beta}} = \frac{\partial C_l}{\partial (\frac{\dot\beta b}{2V_R})}$$

$$C_{l_p} = \frac{\partial C_l}{\partial (\frac{pb}{2V_R})}$$

$$C_{l_r} = \frac{\partial C_l}{\partial (\frac{rb}{2V_R})}$$

$$C_{m_{\dot\alpha}} = \frac{\partial C_m}{\partial (\frac{\dot\alpha \bar{c}}{2V_R})}$$

$$C_{m_q} = \frac{\partial C_m}{\partial (\frac{q\bar{c}}{2V_R})}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{n_{\dot\beta}} = \frac{\partial C_n}{\partial (\frac{\dot\beta b}{2V_R})}$$

$$C_{n_p} = \frac{\partial C_n}{\partial(\frac{pb}{2V_R})}$$

$$C_{n_r} = \frac{\partial C_n}{\partial(\frac{rb}{2V_R})}$$

$\Delta C_{l,r}$ rolling-moment coefficient due to a rudder deflection

$\Delta C_{l,a}$ rolling-moment coefficient due to an aileron deflection

$\Delta C_{n,a}$ yawing-moment coefficient due to an aileron deflection

$\Delta C_{n,r}$ yawing-moment coefficient due to a rudder deflection

$\Delta C_{m,e}$ pitching-moment coefficient due to an elevator deflection

$\Delta C_{y,r}$ side-force coefficient due to a rudder deflection

$\Delta C_{y,a}$ side-force coefficient due to an aileron deflection

$\Delta C_{z,e}$ normal-force coefficient due to an elevator deflection

$\Delta C_{x,e}$ longitudinal-force coefficient due to an elevator deflection

t time, seconds

R_n Reynolds number based on $\bar{c}$

$$l_3 = -\sin\theta_E$$

$$m_3 = \sin\phi_E \cos\theta_E$$

$$n_3 = \cos\phi_E \cos\theta_E$$

n	scale factor
E_s	spin energy factor
M_s	spin moment
R	radius of spin
ν	kinematic viscosity

A dot over a symbol represents differentiation with respect to time.

I. INTRODUCTION

Throughout aviation history the spin has been the cause of innumerable accidents, claiming both lives and equipment. For the designers and pilots of highly maneuverable aircraft (particularly tactical military aircraft) knowledge of the mechanism of this flight regime is important. Unfortunately, it has and still defies complete scientific analysis.

One need only to read accident investigations to understand the scope of the problem. For the months of May and June 1918, one particular type of aircraft in use by the British was involved in twenty-seven (27) spinning accidents, or about six and one-half (6.5) per cent of type inventory [Ref. 112]. The accidents attributable to inadvertent spin became significant for one of our most advanced aircraft, the F-4 Phantom [Ref. 83]. Both the Navy and the Air Force directed investigations as to the cause of these alarming statistics. Thus it can be seen from the above reports that the problem of spin has spanned both design change and time, continually presenting unknown factors which influence the boldness with which the limits of aircraft performance are pursued.

Until about 1916, entering a spin usually resulted in a fatality; there was no known method of recovery. Reference 39 indicates that Mr. H. G. Hawker, piloting a Sopwith, is believed to have developed the recovery method (forward stick,

other controls neutral). Subsequently, Major F. W. Gooden investigated the technique at Farnsborough and published results in 1916. Reference 25, however, attributes the first recorded spin and recovery to F. P. Raynham on September 19, 1911 while penetrating a dense fog bank. In either case, it is generally agreed that deliberate spinning came into prominence only in the latter half of 1916.

For a short time the spin was considered a tactical maneuver to "shake" an opponent. However, as today, the inadvertent spin became an emergency situation. Deliberate spins were performed only in training to ensure pilot competence and confidence in the event of an unintentional spin. Over the years, because of the large number of aircraft lost (particularly jet aircraft), deliberate spins have also been curtailed, except as part of contractor demonstration or research.

Quite obviously the analysis of the spin has been an unattained goal; however, partial understanding is available. This paper is a review of the research effort into the spin phenomenon, particularly as conducted in the United States, and its application to today's aircraft.

II. THE SPIN

If an aircraft is flown into a stall and no corrective action taken, the consequent development of lateral and longitudinal instability reduces flight to a complicated maneuver involving roll, pitch, yaw, and side slip. If allowed to proceed the motion may develop into a spin.

From experience the observed spin motion demonstrates certain generic characteristics. The spin may be either erect or inverted. The normal erect spin is further classified below. The inverted spin is similar to the erect spin except the pilot will undergo negative "G" forces. The major part of spin test results have been directed to the more common erect spin; however, some investigations of the inverted spin have been published [Refs. 67 and 88].

Aircraft motion after the stall, the so-called post-stall gyration, can be summarized as a random gyration consisting of pitching, rolling and yawing oscillations. Incipient spin is defined to be post-stall motion in which a definite rotation pattern is present and, if continued, leads to a developed spin [Ref. 91]. There are three general classifications of the developed spin [Ref. 80].

1. A steady spin is defined as one in which the motion parameters (attitude, rotation, velocity of descent) are time invariant (usually after two (2) to four (4) turns). This steady spin is further classified according to the

angle between the longitudinal axis of the aircraft and the vertical (α), Fig. (1).

a. Steep ($\alpha = 10° - 35°$)

b. Medium ($\alpha = 35° - 50°$)

c. Flat ($\alpha > 50°$)

2. The <u>oscillatory spin</u> is defined as one for which the motion parameters exhibit regular cyclic variations (one cycle not necessarily equaling one turn).

3. An <u>erratic spin</u> is one whose motion parameters are not consistent, or not oscillatory, in regular cycles.

The motion of an aircraft in a spin is actually a specific case of general unsteady motion. The classic aircraft equations must therefore describe the spin. Reference 36 develops the general, stick-fixed equations for unsteady motion [See also Chapter IV of Ref. 37]. The aerodynamic forces can be further modeled with the familiar aerodynamic stability derivatives. The equations of motion used for analytic studies of the steady and incipient spin [Ref. 77] indicate the complex interdependence of inertia forces, inertia moments, aerodynamic moments, and weight (Appendix A). These complex, nonlinear relationships effectively mask the influence of the various parameters on the overall motion. As an aid to visualizing the spin a simplified notion of the spin is in order [Refs. 35, 49, and 50]. A heuristic analysis of the classical steady-state spin developed in Ref. 50, and included, in part, below, provides a prototype from which the salient characteristics of the spin evolve.

The steady-state spin, from observation, is modeled as the helical trace of the aircraft's center of gravity about a vertical spin axis (Fig. 1). The six degrees of freedom of aircraft position and orientation, representing general motion, must therefore be manifested in this idealized spin.

Considering the helical trace fixed in an inertial reference frame (see Fig. 1), the trace of the aircraft center of gravity can be described by vectors A_1, A_2, A_3 obtained from solutions of the equations of motion. The orientation of the aircraft can be described by rotations (θ_E, ψ_E, ϕ_E) about the body-axis system XYZ fixed to the center of gravity.

Just as conveniently, however, the aircraft position can be specified uniquely by transforming the coordinate system to another set of coordinates involving six degrees of freedom. Thus, changing the rectilinear inertial coordinates to a cylindrical system, it is apparent from Fig. 1 that such a set is:

1. Translation along the spin axis
2. Displacement from the spin axis
3. Rotation about the spin axis
4. Rotation about the body X axis
5. Rotation about the body Y axis
6. Rotation about the body Z axis

To motivate understanding of the spin mechanism, consider the following hypothetical experiment. Mount a wing in a vertical wind tunnel at some angle of attack (α) from the vertical axis (Fig. 2a). With the application of some asymmetric disturbance, promoting wing rotation (i.e., roll) about the vertical axis, the upgoing wing - with respect to

the axis of rotation - will experience a decreased angle of attack while the down-going wing will develop an increased angle of attack as a result of the roll. If the initial incidence were well below the stall, the lift on the wings would react similarly; upgoing wing experiencing decreased lift and downgoing wing experiencing increased lift. The overall result is then to provide a damping of the motion. If, on the other hand, the initial incidence were sufficiently above the stall angle, the decrease of angle of attack on the upgoing wing could increase the lift and, conversely, the increased angle of attack on the downgoing wing could develop decreased lift. The result then is a roll in the original direction increasing in speed until the complex aerodynamic forces now generated on the wing sections reach an equilibrium condition of zero moment and a constant roll rate; viz. autorotation.

Applying the implications of the steady-state spin model, Ref. 5 shows that the three force equations can be reduced to a condition requiring the resultant aerodynamic forces to intersect the vertical spin axis. From this assumption it follows that the force components, both vertical and horizontal, must balance weight (mg) and centrifugal force ($mR\Omega^2$) respectively. The three moment equations become

$$1)\quad M_X = (I_Z - I_Y)qr$$

$$2)\quad M_Y = (I_X - I_Z)rp$$

$$3)\quad M_Z = (I_Y - I_X)pq\ .$$

Expressing p,q,r in terms of angles α and β, it can be shown [Ref. 50] that

$$4)\quad M_X = -1/2\ \Omega^2(I_Z - I_Y)\sin 2\alpha\ \sin\beta$$

$$5)\quad M_Y = 1/2\ \Omega^2(I_X - I_Z)\sin 2\alpha\ \cos\beta$$

$$6)\quad M_Z = -1/2\ \Omega^2(I_Y - I_X)\cos^2\alpha\ \sin 2\beta$$

Now consider a complete aircraft model in the wind tunnel with the same wing mounted rigidly to the axis of rotation passing through the center of gravity (c.g.) (Fig. 2b). The tunnel is then set at various speeds V, and the model rotated at various angular speeds (Ω) and angles of attack (α). The spin moment, M_S, required to maintain Ω at different V and α is recorded. With reference to steady spin, the moment about the spin axis must be zero. From the wing test mentioned above, we might expect to find some combination Ω, V_R, and α for which the condition of $M_s = 0$ is satisfied. However experimental evidence indicates this is not generally true for aircraft models. There is usually a need for some externally applied spin moment (M_S) to maintain steady spin rate. Thus the effects of the airflow on the various aircraft components (wings, tail, fuselage) most probably influence the autorotational characteristics in this degree of freedom.

With the model in a steady rotation about the spin axis, there are three moments acting about the Y axis. One is the restraining moment of the model's rigid attachment to the spin axis. Another is the inertia pitching moment resulting from the centrifugal forces of various aircraft components. The third is the resultant aerodynamic forces producing a moment

about the Y axis. Referring to the free spin, the restraining moment must be zero. Thus, by releasing this second degree of freedom, the aerodynamic pitching moment must balance the inertia pitching moment. From equation 5,

$$7) \quad M_Y = -1/2\ \Omega^2 (I_Z - I_X) \sin 2\alpha$$
$$\text{since } \beta = 0$$

Effectively this balance of inertia and aerodynamic pitching moments determines the rotation rate. For a given aircraft the aerodynamic pitching moment is predominantly a result of the tail position relative to the center of gravity. Additionally, the aircraft's mass distribution sets the inertia pitching moment parameter $(I_Z - I_X)$. Substituting these values into equation 7 and specifying stable equilibrium on α, the rotation rate Ω is thus determined [Ref. 50, p. 213]. In particular, small Ω's result from aircraft with heavy mass concentration along the fuselage (a characteristic of modern fighter/attack aircraft).

As a third degree of freedom, the center of gravity is allowed to move radially from the axis of rotation while retaining a symmetric orientation (i.e., plane of symmetry contains the spin axis). Considering the steady rotation rate, equilibrium requires the centrifugal forces to be balanced by the horizontal component of the air reactions. With Ω and α previously specified, the spin radius R and the total aerodynamic force must develop to balance the equation.

Experience indicates that since the resultant aerodynamic force acts approximately perpendicular to the wing chord

through the c.g., the radial c.g. shift is such that the pilot maintains a view toward the spin axis and the resultant aerodynamic force (normal to the wing chord) must then usually be orientated so as to intersect, or very nearly intersect, the vertical spin axis. Deviation of the wing span from the horizontal may be regarded as rotation of the aircraft about the Z body axis (normal to the wing chord through the c.g. and intersecting the spin axis). Therefore rotation about the X body axis, the fourth degree of freedom, is not of great significance.

As a consequence of this c.g. movement from the spin axis there is, by the usual definitions of sideslip, a resultant sideslip due to the horizontal component of ΩR, i.e., $\beta \cong \sin^{-1} \frac{v}{V} = \frac{\Omega R}{V}$. Thus, in a right-hand erect spin (clockwise, viewed from above), β would be to the left, and conversely.

Experimental evidence has indicated that sideslip will produce a large pro-spin moment and thus increase the spin rate, for left slip in a right spin, and vice versa. The tail and fuselage, as shown below, provide the anti-spin aerodynamic balance.

Permitting rotation (yaw) about the Z body axis is the fifth degree of freedom and an additional source of sideslip. Yaw to the right, for example, provides sideslip to the left, and conversely. Sideslip from yaw and radial c.g. movement are arithmetically additive when the yaw and the spin rotation

are in the same direction. Consequently the equilibrium about the Z body axis is important.

The aerodynamic yawing couple about the Z axis is balanced by the inertia yawing couple (equation 6). The principal yawing moments come from the wing, fuselage, and tail. The wing yawing moment depends on the wing design and the spin conditions. The aerodynamic yawing moment due to the fuselage rotation depends on the fuselage cross-section. Finally the aerodynamic moment due to the tail are determined by placement and shielding effects.

If the aircraft has a mass distribution predominantly along the wing, then I_X is large. Further, if the combination of spin and yaw is such that the leading wing is above the horizon, the resulting inertia couple on the wing is applied in a direction to return the wings to the horizontal, an anti-spin couple (reducing the sideslip). If however, the wing is tilted leading leading wing down, the couple would be pro-spin.

If the aircraft had been mass loaded primarily along the fuselage (large I_Y) and the leading wing were up, the applied couple would be pro-spin by tending to rotate the fuselage against the spin (and conversely for outer wing down). Thus from equation 6 the difference $(I_Y - I_X)$ is clearly influential in the spin.

Since, in general, experience has indicated that the leading wing up is the prevalent tendency, the wing has an anti-spin effect, and the tail and fuselage have a pro-spin effect.

The final degree of freedom is to allow the model to move vertically. Since the resultant aerodynamic force is considered to act perpendicular to the chord, the velocity of descent must be related in the steady spin as follows:

$$mg = F\sin\alpha = C_F \; 1/2\rho V^2 S\sin\alpha$$

thus V is determined.

Note that sideslip now also influences the moment about the spin axis. Thus, as first proposed, if the M_s is reduced to zero by the function of sideslip, there will be equilibrium conditions throughout the system and in fact, an autorotative state: the classical steady-state spin.

III. RESEARCH

What are the questions the spin researcher is trying to answer? Obviously two points of view must be considered, the designer's and the pilot's. A casual examination might, at first, suggest a simple answer. To provide safety (no inadvertent spins and rapid recovery), the designer should design ample margins for those parameters which previous experience indicates contribute to satisfactory characteristics. However, in quest of performance the question of spinning has been forced into the background and consequently the designer's latitude is limited. What then is the design criterion? The parallel goal is to determine the best recovery procedure for a given design. For this an accurate estimate of full-scale aircraft characteristics is a necessity. With these two goals in mind, research into the spin has been conducted.

One avenue to understanding the influence of various design and control factors is to theoretically formulate the interaction of air flow and aircraft at high angles of attack. The obstacle to this analytic approach is the lack of a complete understanding and representation of the airflow for a stalled aircraft. This procedure would be most desirable as it would provide à priori knowledge at all stages of investigation. The most direct method to develop the required aerodynamic forces is simply to build the proposed full scale

aircraft and conduct flight tests. This is obviously an impractical scheme except in the case of the end product. A third approach is to develop a method to simulate the interaction of forces with direct correlation to the full scale aircraft.

Each of these three approaches have been utilized in the continuing research into the phenomena of spin. The following paragraphs outline these research techniques and their uses.

The primary research tool for spin investigations has been the spin tunnel test of free-spinning dynamic models.

About 1931, investigators developed a procedure [Ref. 99] to investigate the spinning characteristics of dynamically scaled models [Ref. 94] launched from the top of a balloon shed. This method was discontinued in light of significant question as to the fidelity of the observed motion (and short test drop).

Research in the United States consisted of studying the effects of various components by measurements of the aerodynamic forces and moments on the spinning airplane. Measurement of these were made in the Langley five-foot vertical tunnel [Refs. 3-13].

The British, however, who adopted the research technique of free spinning tests [Ref. 100], subsequently refined it to the use of a small vertical wind tunnel and in 1932 a twelve foot diameter spin tunnel was put into operation. The promising results of the British prompted National Advisory Committee for Aeronautics (NACA) to develop their own

capability and in 1935 a 15-foot diameter spin tunnel was put in operation [Ref. 111]. In 1941 the facility was expanded to a 20-foot diameter tunnel [Fig. 3].

The testing procedure consists of launching a dynamically scaled model, by hand, into a vertically rising airstream. The model initially enters the airstream at a high angle of attack (above stall) and rotation establishes a rate with the control surfaces in a pro-spin position. The airstream speed is adjusted by an operator so that the rate of descent is balanced and the model reaches a developed spin at a constant height. After observing the spin, the controls are remotely activated in various combinations to effect recovery [Refs. 89, 111]. During the maneuvering of the dynamic model, motion picture cameras record the motion. One camera is mounted vertically upward and the other horizontally with the model. From the photographic records the time histories of the model's attitude and velocities are developed [Ref. 89].

Spin-tunnel testing is conducted to determine spin and recovery characteristics with normal control configurations for spinning (elevator full up, lateral controls neutral, rudder full with the spin) and various other control settings. Recovery is generally initiated either by rapid full rudder reversal, by reversal of both rudder and elevator, or with both rudder and aileron full with the spin. The tests range over all possible loading conditions. Tests to evaluate any possible adverse effect on recovery for small deviation from normal control are elevator two-thirds full up and lateral

controls one-third full deflection in the direction of slower recoveries (direction depending on mass characteristics). Recovery is attempted by rudder reversal to two-thirds against spin, elevator neutral or two-thirds down, or two-thirds rudder against spin and stick two-thirds with spin. These controls are considered the "criterion spin." A satisfactory recovery is achieved if recovery from the "criterion spin" is completed within two and one-fourth (2-1/4) turns. This requirement is based on correlation of past wind tunnel and flight test data [Ref. 59].

Spin-tunnel testing relies on the correlation of model to aircraft spin and recovery characteristics. The factors which influence the fidelity of this correlation are of significance.

Dynamically similar systems are ones which move in response to forces such that the time histories of component relative positions are geometrically similar. A free-flying dynamic model is required to reproduce the motions of full-scale aircraft with a geometrically similar flight path and the attitudes (angle of incidence, bank, and sideslip) of the model and of the aircraft identical. Thus the ratio of inertia forces to aerodynamic forces must be maintained the same between the full-scale aircraft and the model.

Reference 82 develops the following set of ratios for dynamic models such that the inertia forces and moments are maintained to scale.

The relationship between the model and aircraft are

Unit	Dimension	Scale Ratio (model/aircraft)
Length	l	$1/n$
Mass	m	$1/n^3\sigma$
Time	t	$1/n^{1/2}$
Linear velocity	l/t	$1/n^{1/2}$
Angular velocity	$1/t$	$n^{1/2}$
Moment of inertia	ml^2	$1/n^5\sigma$

The aerodynamic forces and moments however, are not so convenient. Examination of the ratio of Reynolds number (model (m) to aircraft (a))

$$R_n = Vl/\nu$$

$$\frac{(R_n)_m}{(R_n)_a} = \frac{V_m l_m}{\nu_m} \cdot \frac{\nu_a}{V_a l_a}$$

$$\frac{(R_n)_a}{(R_n)_m} = \frac{\nu_a}{\nu_m} \left(\frac{1}{n}\right)^{3/2}$$

indicate the change in Reynolds number is a large one. Thus there has been need to investigate the effects of Reynolds number variation on the test results. Reference 81 observed the effects on two-dimensional noncircular cylinders, in low speed flow, of variation of incidence and Reynolds number. This variation demonstrated large effects on drag and side-force; and of particular note was the sign change of side-force with Reynolds number variation. These results imply considerable significance for, in particular, dynamic model tests in the spin tunnel. By empirical methods [Refs. 1 and 29] the effects of fuselage were investigated. Reference 83

investigated a hypersonic research aircraft model to determine the critical Reynolds number and found that as suggested the nose section can exert either a propelling or damping influence on the yawing moment. Reference 64 indicates that the cause of this increase in yawing moment with angle of attack is due to the asymmetrical disposition of a pair of trailing vortices emanating from the nose section. From these investigations, quite clearly, the application of test results from the spin tunnel must be applied with an appreciation of the above factors when attempting to extrapolate the empirical test results to the full-scale spin predictions.

A further criticism of the free spinning tunnel is the manner in which the model is launched. There is a possibility that by launching above the stall the model may be in a spin mode which could not be attained from normal flight entry conditions.

Nevertheless, by far the most productive research tool has been the free-spinning tunnel. Due to the response dependence on the design parameters of the particular model, the main thrust of spin tunnel research has been analysis of the behavior of particular aircraft designs in the attempt to determine the optimum technique for recovery and the effects of various configurations. References 15 and 50 provide an incomplete list of aircraft designs tested and their comparison with full scale results. For the period 1926 to 1948, Ref. 15 discussed sixty designs spanning the range from biplane to swept-wing aircraft. Of the sixty models tested, fifty-three

recoveries corresponded with the actual aircraft; three had optimistic prediction; four had conservative predictions. The overall accuracy was 90 per cent. Reference 59 developed a comparison between twenty-one further designs of the 1950-1960 period. These results showed 19 of 21 tests to be in good agreement and two with significant differences. The store of knowledge gained in these experiments forms the basis from which the model test data are extrapolated to full scale predictions: "The art of evaluating the meaning to these results in light of previous model results and corresponding full-scale results" [Ref. 59].

Of current interest is the investigation of the jet trainer T-2 Buckeye [Ref. 20], light aircraft design [Ref. 54] and light propeller-driven military aircraft [Ref. 61 and 62]. Tests on two military aircraft of particular significance (the operational losses from spinning accidents has prompted investigation), the A-7 [Ref. 63] and the F-4 [Ref. 31]., are also being conducted.

As noted above the characteristics of various parameters of the aircraft have significant influence. As performance requirements changed, high speed design concepts generated several configuration parameter changes on the aircraft wings. The effects of these changes were reviewed in several reports. Reference 85 investigates the effect of wing sweep on the spin. In general, sweep (it is concluded) can have a tendency to improve the recovery characteristics of some designs which show unsatisfactory characteristics, and little effect on designs which showed good recovery.

During the same time period, leading edge slots were incorporated to improve stalling or increase speed range. Several British reports indicated a large influence on the spin regime. As a result, Ref. 72 investigated the influence of slots, concluding that leading edge slots may have pronounced effect on the recovery from a spin. In particular, for an aircraft primarily mass loated along the wings, slots would have an adverse effect, i.e., flatter and lower rate spins; the converse holds for fuselage-heavy aircraft.

Reference 109 further investigates wing leading-edge chord-extensions and drooped leading-edge flaps which were suggested as means of improving the longitudinal stability characteristics of aircraft with swept wings along with improvement of maximum lift coefficient. It was found that undrooped chord-extensions had no appreciable effect on model spin. However, drooped chord-extensions could be beneficial.

The use of spoilers-slot-deflectors was investigated in Ref. 46 as a means of lateral control and its effect on spin, with the conclusion that "effectiveness of any proposed spoiler-slot-deflector configuration will have to be evaluated for each configuration."

Some interest in canard aircraft was noted and therefore the effects of this design were evaluated with respect to the spin [Ref. 79]. Results indicated that the spin motion for the design tested were similar to conventional aircraft. With the fairly flat spins the rudder was effective in recovery primarily due to the fact that it was apparently unshielded.

Also, moderate changes in mass distribution and vertical tail size did not alter spin characteristics.

Reference 38 reviewed the effects of flaps and landing gear. Considering the results of a number of tests, the report concluded that extending flaps usually had an adverse effect on the spin recovery; except that no effect on aircraft heavily loaded along the fuselage was noted. The landing gear caused increased inward sideslip and angle of attack but no effect on recovery.

One of the critical factors evident in the equations of motion is mass distribution. The significance of this parameter was recognized early with experimentation as to the effects of variations in moments of inertia on spin [Ref. 74]. This parameter has been significantly altered due to modern design trends (which included placing jet engines in the fuselage, long nosed fuselage, and thin swept wings to name a few) [Ref. 76]. The moments of inertia about the Y and Z axes are 10-20 times as large today as in the era of WWII. See Fig. 4 for a comparison of these values. The parameters as they arise in the equations are:

$I_X - I_Z$ = inertia pitching moment, predominates with fuselage loading.

$I_Y - I_Z$ = inertia rolling moment, predominates with wing loading.

$I_X - I_Y$ = inertia yawing moment.

Early investigation as to the mass center of gravity was presented in Ref. 69 for a range of aerodynamic characteristics.

Reference 70 clearly indicates the influence of mass distribution. A review of five years of model spin testing covering a wide range of design dimensions exhibited a consistent difference in spin and recovery characteristics. This difference was evident between aircraft heavily loaded along the fuselage and those heavily loaded along the wings. The spin motion observed with heavy fuselage loading has changed from the relatively steady to an oscillating motion in roll and yaw.

The product of inertia which is usually neglected in calculations is investigated in Ref. 3. The increase of product of inertia may increase the degree of oscillation during the spin entry. But, in general, the nature of the developed spin was not altered.

The aircraft mass characteristics further are in the equations in the form of the aircraft relative density. Ref. 42 made an analytical study of the effects of the relative density ($\mu = W/g\rho Sb$). The only generalization which was made was that relative density caused increased roll oscillations during spin entry while other effects were inconsistent.

Design trends of tactical military aircraft (high speed configurations with long slender fuselages and predominant fuselage loading) in conjunction with spin tunnel experience indicated that recovery from the full developed spin might be exceedingly difficult and, due to the significant concomitant altitude loss, may be only of academic interest. As noted previously, however, the spin tunnel investigations required

"interpretation" with respect to the actual aircraft due to the Reynolds number effect and launching technique. Experience indicated that this generic design trend in fact actually tended to delay the fully developed spin. Thus, interest was focused on the incipient spin and the conjecture that control manipulation might terminate the gyrations prior to the fully developed spin; and the investigation of incipient spin required a new research tool.

One attempt to observe the incipient spin was the catapulting of dynamic models into still air [Refs.22, 106]. However, due to space limitations and scale effect, a test with more direct correlation was required.

NASA Langley formulated a technique utilizing a radio controlled-dynamic model [Refs.65, 66]. The free-falling model was dropped from a helicopter (about 3,000 feet, 60KTS) and controlled by two (2) ground observers. This procedure allowed testing at Reynolds numbers (based on aerodynamic chord) of 790,000 to 960,000 and, thus, suitable comparison with the full scale aircraft. The flights were recorded by both ground cameras and a model-mounted camera.

An example of the use of wind tunnel and radio-controlled data for an F-104 is included in Ref. 60. The dynamic model test results are found to correlate well with the actual aircraft.

Research and evaluation of spin and recovery characteristics was based on the empirical test results of both spin tunnel and full scale flight through the early 1950's.

Requirements to optimize operational capabilities and the consequent design evolution resulted in observed spin motions which deviated from the classical steady spin to one of cyclic oscillations (primarily in roll and yaw) [Ref. 105]. Also, the fidelity of dynamic model motion decreased. Short of reliance on full scale testing, one available alternative involved theoretical analysis to develop a priori the influence of design on spin models and to pinpoint any possible critical spin condition.

Most generally, this approach involves the mathematical modeling of the aircraft motion and aerodynamic data. The standard Euler equations of motion represent the motion without any seriously restrictive assumptions. The aerodynamic factors are another matter. One needs to describe the behavior of an aircraft in the resultant flow field at high angles of attack and sideslip. Thus far, the complicated flow patterns have defied any attempts to predict aerodynamic forces and moments. Reference 44 surveys the on-going research of both the aerodynamic and dynamic behavior of aircraft at the stall.

An entirely theoretical approach was attempted in Ref. 25. Some initial step-by-step calculations have been attempted.[1]

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[1] Unpublished reports: Analysis of Motion of an 'SE5' Aeroplane by Step-by-Step Integration, by F. Workman, 1924; and Investigation of Combined Lateral and Longitudinal Motions of an Aeroplane, by A. V. Bainoff and L. Huff, 1929. Original in German, Loftfahrtforschung, translated into English for BARC(SPIN22).

An approach in which the aerodynamic derivatives were assumed to be constants is presented in Ref. 26. These early attempts, however, suffered from a lack of precise aerodynamic data.

In the absence of a mathematical approach, the development of a rotary balance testing procedure provided a means by which the empirical determination of aerodynamic forces and moments could be made. The rotating portion of the balance when placed into the center of the test section, has adjustable spin rate, spin radius and attitude. A six-component strain gauge balance measures normal, longitudinal, and lateral forces and rolling, pitching and yawing moments about the body axes. A complete description of the rotary balance is included in Ref. 105.

Data from the rotary balance provided the basis for step-by-step hand calculations of the spin motion, presented as a series of time-history plots [Ref. 39]. Reference 28 further expands this approach.

With the advent of computer technology these calculations were carried out on analog and digital computers. The computers initially available were not versatile enough to incorporate parametric variation; thus, the aerodynamic data were partially linearized and presented as a function of angle of attack.

Reference 110, independently, develops a technique utilizing static aerodynamic data to obtain estimates of rotary and damping derivatives based on strip theory. In an attempt to remove the problem of Reynolds number influence, a "grit tripping" procedure was incorporated to simulate high Reynolds numbers

effects in a low Reynolds number flow. Reference 45 extends this approach and develops a method of rapidly determining regions of angles of attack and sideslip for which a steady spin might occur.

The use of the high-speed digital computer to study aircraft spinning motion appeared to be an important adjunct to research and various investigations have been conducted. Reference 90 investigates the effects of differences in full-scale and spin-tunnel testing. The test concluded that different spin modes are possibly obtainable from level flight entry as opposed to the spin-tunnel launching technique.

Reference 87 used the analytic approach to investigate or simulate a known aircraft spin entry, developed spin, and recovery motions, as did Ref. 45. Both were reasonably able to simulate the full scale test motions. Reference 41 uses both low Reynolds number aerodynamic data and high Reynolds number data. Calculations from the low Reynolds number data are considered in good qualitative agreement with free-spinning tunnel tests; with high Reynolds number data, the aircraft was found to resist spin entry (however, it would spin if launched into the spinning condition). It concluded that with relatively large amounts of nose down aerodynamic pitching, large amounts of effective dihedral ($C_{l\beta}$) are required to enter and maintain a spin. Also, the value of pitch damping (C_{mq}) can make a difference in spin entry and this quantity would be carefully measured. These three factors then can be the difference between spin or no spin. A non-dimensional spin-energy

$$E_s = 1/2\ I_V\ \Omega^2 / 1/2 \rho V_R^2\ Sb$$

parameter was introduced in Ref. 2 as an indicator of the relative difficulty of spin recovery. This analytic study varied C_n; increased C_n caused more rapid rotation and higher angles of attack and E_s. Changes in C_l had very little effect on spin conditions. Increasing negative aerodynamic pitching moment increased rotation rate and E_s. Recoveries were calculated by applying constant external yawing and rolling moments. Increasing anti-spin yawing caused faster recoveries. For negative $(I_X - I_Y)$ positive applied rolling moment led to faster recoveries. Thus the report shows a correspondence between anti-spin yawing-moment coefficient required for satisfactory recovery and the spin energy factor. Further the anti-spin rolling moment required for satisfactory recovery was found to be related to both the spin energy factor and I_X.

Recently, Ref. 18 made an inclusive study of the degree of influence of various quantities on the spin. The study investigated non-aerodynamic characteristics, static aerodynamic characteristics, and the dynamic aerodynamic properties by gross adjustment of these various parameters. A set of time histories is presented in Ref. 18.

This parametric study concluded that the dynamic derivatives were not of appreciable influence on the spin, i.e., only the non-aerodynamic and static properties were important from the pilot's point of view, with the exception of the damping in pitch (C_{mq}).

The most direct method of spin research is to fly the actual aircraft to determine its characteristics. In fact, just this procedure brought about realization of the spin problem. Due to the nature of spins, as indicated in the introduction, the only available data were from observation and an occasional survivor. Major Goodden was the first pilot to intentionally spin an airplane in 1916. Following this, Dr. F. A. Lindemann directed the first scientific experiments into the problem [Ref. 39]. These flight tests developed original information on path and attitude, establishing:

1. Path as a steep helix of radius 10-20 feet.
2. Attitude such that the central portion of wings are above the critical angles of attack.
3. Speed of aircraft is approximately equal to the descent rate.

These tests further indicated the importance of rudder control. Additional experiments were conducted by Major R. M. Hill. Starting with an aircraft which had been found to be unspinnable, he gradually removed fabrics from the vertical fin, achieving a spinnable configuration. Further, he determined that decreasing the aspect ratio reduced the longitudinal stability and enhanced the ease of spin entry.

Full scale spin is the culmination of a modern spin program. Its aim is to demonstrate the spin characteristics of a specific design and its ability to recover satisfactorily. The requirements for a spin demonstration of the Navy, for example, are:

". . . shall be adequate to provide consistent prompt recoveries from fully developed erect and inverted spins. Recovery shall require no abnormal effects on the part of the pilot. . . . spin recovery characteristics shall be adequate to permit spin demonstration as required by the procuring activity . . . "[2]

The full scale spin is undertaken only after a careful build-up of information from the supporting phases of the spin test program. These are:

a. Wind tunnel data acquisition
b. Analytic studies
c. Free-spinning tunnel tests
d. Radio control model tests
e. Fixed base simulation.

With data from these tests, the aircraft manufacturer conducts full-scale tests to demonstrate recoverability. Following contractor demonstrations, the service test pilots evaluate the recovery characteristics and contractor findings. For example, see Refs. 35, 52, and 84.

References 78 and 81 discuss in detail the consideration to be made in order to reduce the inherent dangers of spin testing. Prior to actual spinning, the aircraft should be flown at high angles of attack simulating entry conditions to investigate the possible effects of:

a. Aircraft configuration
b. Mass characteristics
c. Structural considerations
d. Control system characteristics
e. Emergency hydraulic and electric power
f. Engine considerations

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[2] Military specifications MIL F-8785(AS6)

g. Pilot experience

h. Instrumentation

on the spin and recovery characteristics.

Of particular importance to the safety of the test program is the anti-spin device, which must be capable of inducing satisfactory recovery from any possible spin mode. The two available spin systems used in spin test work are "spin-chutes" and rockets.

The "spin-chute" is the most commonly used anti-spin device. The effects of the "spin-chute" on recovery are determined experimentally in the spin tunnel tests, for example Ref. 31. The requirements and general character of the "spin-chute" are reviewed in Ref. 86. One major drawback of the system is that the mounting area, usually the tail section, must be reinforced to withstand the impact loads of the chute opening.

The second means of recovery is the mounting of a solid rocket either at the wing tips (anit-spin yawing moment) or aft fuselage (yawing and pitch-down moment). This technique of using a reactor was originally reported in Ref. 47. NACA further investigated the method [Ref. 52]. From indications that the method would be workable, Ref. 26 compared dynamic model with full scale results and found good agreement. This method eliminates high impact loading caused by the "spin-chute," but adds considerable weight to the aircraft. As an example of the use of reactors, the OV-10A spin characteristics were investigated in Ref. 52 using wing-tip mounted rockets.

The ability of the pilot to recover from a spin is, needless to say, of great interest. The effectiveness of any control in bringing about recovery depends on the effectiveness of control induced moments in upsetting the spin equilibrium by changes in angular velocity. The relative effectiveness of pitching, rolling and yawing moments depend upon the mass distribution and the particular control deflections for optimum recovery. Considerable research has been directed to the relationahip of design parameters.

Because of the influence of yawing moments in terminating the spin, the tail has received considerable study. Reference 73 presents a method of designing satisfactory spin recovery based on empirical relationship between the damping factor (the product of tail damping ratio and unshielded rudder-volume coefficient) and mass distribution. Covering a range of aircraft designs, an empirical relationship for a satisfactory recovery to set design requirements for an airplane is developed.

The effect of tail length is investigated in Ref. 53 showing that regardless of tail damping factor, longer tail lengths had better recovery characteristics than indicated by the tail damping factor alone.

References 2 and 4 attempt to develop a direct relationship between the number of turns during a recovery and the applied moments. While Ref. 2 assumes a linear relationship, Ref. 4 develops multiplicative and exponentional nonlinear forms for steady recovery motions.

Several reports were developed in an attempt to make light aircraft recoverable from a spin by releasing the controls. Design requirements of Ref. 71 for recovery from a fully developed spin for light plane tail surfaces is noted in Ref. 73.

Since the forces involved are of considerable importance, the correlation of control forces with tail design effects is considered [Refs. 102 and 103]. The rudder hinge moment coefficients are investigated in Refs. 16 and 17. Reference 38 considers the effectiveness of adding an extension to the horizontal stabilizer (anti-spin fillet) and is found to be effective in changing the tail damping power.

Along with a demonstration of aircraft's ability to recover from spin conditions, measurement of the various parameters are of importance in the correlation of full scale flight tests and model analysis predictions.

Reference 67 indicates some of the early attempts at recording the necessary data. References 78, 80, and 59 present information on the aircraft and ground instrumentation applicable to the measurement:

a. Number of turns in the spinned turns for recovery
b. Position of all movable controls
c. Angle of attack at center of gravity
d. Angle of sideslip at center of gravity
e. Resultant velocity
f. Angular rates about three axes
g. Altitude
h. Earth - reference attitude angles
i. Linear acceleration
j. Angular accelerations

k. Pilots comments

l. Film record

From this information, data reduction provides time-histories for investigation and correlation with previous analysis/model tests.

IV. CONCLUSION

As has been demonstrated, the spinning of an aircraft is a particularly complicated motion. In general, the developed spin is described by a mean wing incidence greater than stalling, rotation about a near vertical axis, and the center of gravity descends with a linear velocity. While the spin has lost any practical usage, the all too frequent inadvertent spin is a significant problem which cannot be overlooked in the design and use of modern aircraft. This generation of aircraft must demonstrate an acceptable ability to terminate the spin. Since the pilot has only the usual aerodynamic controls available, their effectiveness must be ensured; enabling the pilot to fly his aircraft to its limits with confidence. Because of the limits of performance criteria, there is need to determine the margins of acceptability of the controls with regard to the spin during the design stage. Since the size of these controls have remained about the same dimensions over the years while mass distribution has radically changed, prediction confidence is limited. While the steady spin was reasonably terminated in older aircraft, modern aircraft have proven difficult (particularly the steep or flat spin). Thus, there is interest in understanding the incipient spin and the possibility of terminating potential

spin motion by proper control application; or perhaps, spin avoidance by understanding the transition from normal flight to developed spin.

The major problem in determining these approaches is the requirement for a model or a means of formulating predictions. The basic tools outlined above are:

a. Spin testing of dynamically scaled models in the Langley Spin tunnel

b. Spin tests of radio-controlled free-flight models.

c. Computer analytical studies.

These techniques derive a measurement of the effectiveness of various design parameters and controls.

While these methods have provided significant information for the steady spin, and a lesser extend the incipient spin, a satisfactorily precise predictive method has not developed. The designer has not been able with full confidence to anticipate the spin characteristics. Thus, full scale flight testing, with the guiding insight gained from the build up tests, is required to at least ensure recovery from deliberate and controlled conditions. The spin program has primarily been a design by design consideration based on insight gleaned from years of experience. A definite design criteria has yet to emerge. Excellent reviews of aspects of the spin problem are contained in Refs. 51, 58, and 77.

These techniques, with the exception of the computer studies, are based on completed designs. Reference 32 reviews techniques which are available to the designer to

determine stall and spin characteristics and modify, if necessary. In the early design stage these include:

a. Conventional wind tunnel tests
b. Fixed base simulation
c. Analytical studies

Application of wind tunnel test to the spin problem [Ref. 31] isolate the factors which cause the flat or steep spin and identify the possible autorotative conditions [Ref. 33]. The rotary-balance [Ref. 105] is useful in defining the non-linear trends of aerodynamic moments with spin rate. The more conventional static wind tunnel can also be applied to obtain yawing moment change with sideslip. These tests however, require interpretation with respect to the air flow conditions at the tail.

The fixed base simulator is an attempt to overcome the lack of pilot input. Two basic flight regimes neglected in the previously mentioned tests:

a. No information regarding the susceptability of the aircraft to spins in a tactical environment.

b. No detailed information on the aspects of aircraft control ability at high angles of attack.

This method, while proving feasible, suffers from the need of complete aerodynamic data for the aircraft. If this data is available, the aircraft flight conditions are simulated using limited visual, kinesthetic, and aural cues [Ref. 68].

The analytical studies, while having outstanding possibilities for spin prediction [Refs. 42, 104], show poor

correlation has existed between theoretical predictions and model tests [Ref. 32]. Partial explanation for this is found in the random non-repeatable asymmetric yawing moments. As mentioned earlier, there is asymmetric shedding of vortices from the nose of some types of aircraft as a probable cause of this phenomenon.

Spin research is an on-going research topic. While NASA has been the primary investigator in this country, the problem has received attention in other countries interested in aircraft manufacturing [Refs. 37, 51, 58] and they reportably [Ref. 44] have the same general conclusions. Presently in this country, the United States Air Force has formed a team to study the spin. There are several contracts in existence, one of particular interest is an attempt to change the form of modeling the aerodynamic force, i.e., something other than the derivative formulation.

Another avenue which might have some validity would be the use of Liapunov stability functions. This method examines the stability of differential equations without the use of explicit solutions. Description of the stability criteria indicates possible application to a spinning aircraft. In researching this possibility only one application could be found.[3] However, a translation was not available.

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[3] N. G. Chetaev, Concerning Stability of Motion, Izv. AN SSSR, Division of Technical Sciences, No. 6, 1946.

APPENDIX A

SPIN EQUATIONS

The following equations of motion [Ref. 77] are used in the analytical study of spin-recovery motions of an aircraft.

$$\dot{u} = \frac{V^2}{2\mu b} C_X + g l_3 + vr - wq$$

$$\dot{v} = \frac{V^2}{2\mu b} C_Y + g m_3 + wp - ur$$

$$\dot{w} = \frac{V^2}{2\mu b} C_Z + g n_3 + uq - vp$$

$$\dot{p} = \frac{V^2}{2\mu k_x^2} C_l + \frac{I_Y - I_Z}{I_X} qr$$

$$\dot{q} = \frac{V^2}{2\mu k_y^2} C_{m,b} + \frac{I_Z - I_X}{I_Y} rp$$

$$\dot{r} = \frac{V^2}{2\mu k_z^2} C_n + \frac{I_X - I_Y}{I_Z} pq$$

$$l_3 = -\sin\theta_E$$

$$m_3 = \sin\phi_E \cos\theta_E$$

$$n_3 = \cos\phi_E \cos\theta_E$$

$$\dot{l}_3 = m_3 r - n_3 q$$

$$\dot{m}_3 = n_3 p - l_3 r$$

$$\dot{n}_3 = l_3 q - m_3 p$$

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V_R}$$

The equations of motion being used for incipient spin studies are as follows:

$$\dot{p} = \frac{I_Y - I_Z}{I_X} qr + \frac{I_{XZ}}{I_X}\dot{r} + \frac{I_{XZ}pq}{I_X} + \frac{\rho V_R{}^2 Sb}{2I_X} C_{l_\beta}\beta + \frac{\rho V_R Sb^2}{4I_X} C_{l_p} p$$
$$+ \frac{\rho V_R Sb^2}{4I_X} C_{l_{\dot{\beta}}} \sin\alpha\dot{\beta} + \frac{\rho V_R Sb^2}{4I_X} C_{l_r} r - \frac{\rho V_R Sb^2}{4I_X} C_{l_{\dot{\beta}}} \cos\alpha\beta$$
$$+ \frac{\rho V_R{}^2 Sb}{2I_X} \Delta C_{l,r} + \frac{\rho V_R{}^2 Sb}{2I_x} \Delta C_{l,a} + \frac{F_{Z,roc}y}{I_X}$$

$$\dot{q} = \frac{I_Z - I_X}{I_Y} pr + \frac{I_{XZ}}{I_Y} r^2 - \frac{I_{XZ}}{I_Y} p^2 - \frac{I_{X,eng}\omega_{eng}}{I_Y} r$$
$$+ \frac{\rho V_R{}^2 S\bar{c}}{2I_Y} C_m + \frac{\rho V_R S\bar{c}^2}{4I_Y} C_{m_q} q + \frac{\rho V_R S\bar{c}^2}{4I_Y} C_{m_{\dot{\alpha}}} \dot{\alpha}$$
$$+ \frac{\rho V_R{}^2 S\bar{c}}{2I_Y} \Delta C_{m,e} - \frac{F_{Z,roc}x}{I_Y}$$

$$\dot{r} = \frac{I_X - I_Y}{I_Z} pq + \frac{I_{XZ}}{I_Z}\dot{p} - \frac{I_{XZ}}{I_Z} qr + \frac{I_{X,eng}\omega_{eng}}{I_Z} q$$
$$+ \frac{\rho V_R{}^2 Sb}{2I_Z} C_{n_\beta}\beta + \frac{\rho V_R Sb^2}{4I_Z} C_{n_r} r - \frac{\rho V_R Sb^2}{4I_Z} C_{n_{\dot{\beta}}} \cos\alpha\dot{\beta}$$
$$+ \frac{\rho V_R Sb^2}{4I_Z} C_{n_p} p + \frac{\rho V_R Sb^2}{4I_Z} C_{n_{\dot{\beta}}} \sin\alpha\dot{\beta} + \frac{\rho V_R{}^2 Sb}{2I_Z} \Delta C_{n,r}$$
$$+ \frac{\rho V_R{}^2 Sb}{2I_Z} \Delta C_{n,a} - \frac{F_{X,roc}y}{I_Z} + \frac{F_{X,roc}x}{I_Z}$$

$$\dot{u} = -g \sin\theta_E + vr - wq + \frac{\rho V_R{}^2 S}{2m} C_X + \frac{\rho V_R{}^2 S}{2m} \Delta C_{X,e} + \frac{T}{m} + \frac{F_{X,roc}}{m}$$

$$\dot{v} = g \cos\theta_E \sin\phi_E + wp - ur + \frac{\rho V_R{}^2 S}{2m} C_{Y_\beta} \beta + \frac{\rho V_R Sb}{4m} C_{Y_p} p + \frac{\rho V_R Sb}{4m} C_{Y_{\dot{\beta}}} \sin\alpha\dot{\beta} + \frac{\rho V_R Sb}{4m} C_{Y_r} r - \frac{\rho V_R Sb}{4m} C_{Y_{\dot{\beta}}} \cos\alpha\dot{\beta} + \frac{\rho V_R{}^2 S}{2m} \Delta C_{Y,r} + \frac{\rho V_R{}^2 S}{2m} \Delta C_{Y,a} + \frac{F_{Y,roc}}{m}$$

$$\dot{w} = + g \cos\theta_E \cos\phi_E + uq - vp + \frac{\rho V_R{}^2 S}{2m} C_Z + \frac{\rho V_R{}^2 S}{2m} \Delta C_{Z,e} + \frac{F_{Z,roc}}{m}$$

APPENDIX B

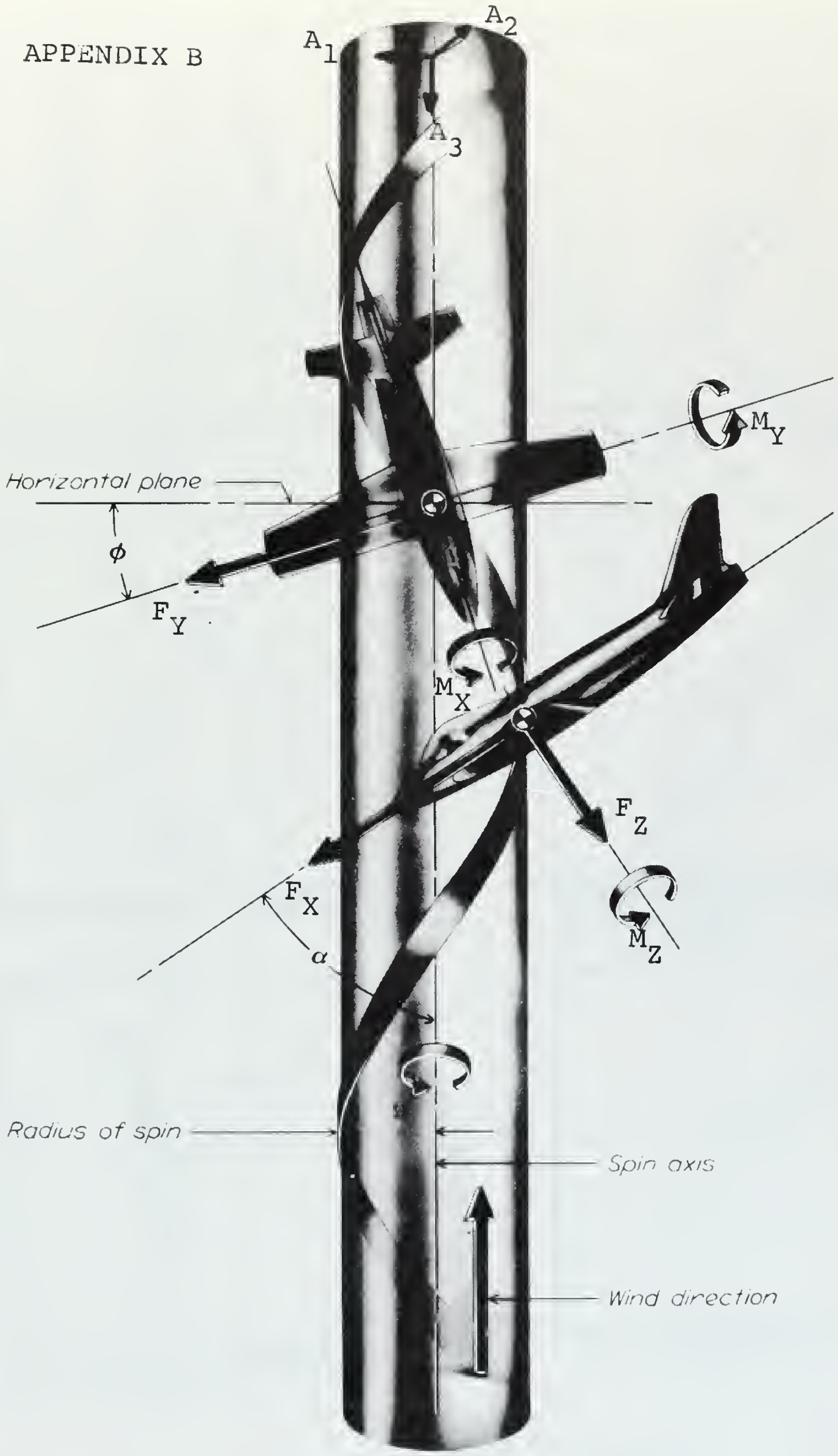

Figure 1. The Spin [Ref. 38].

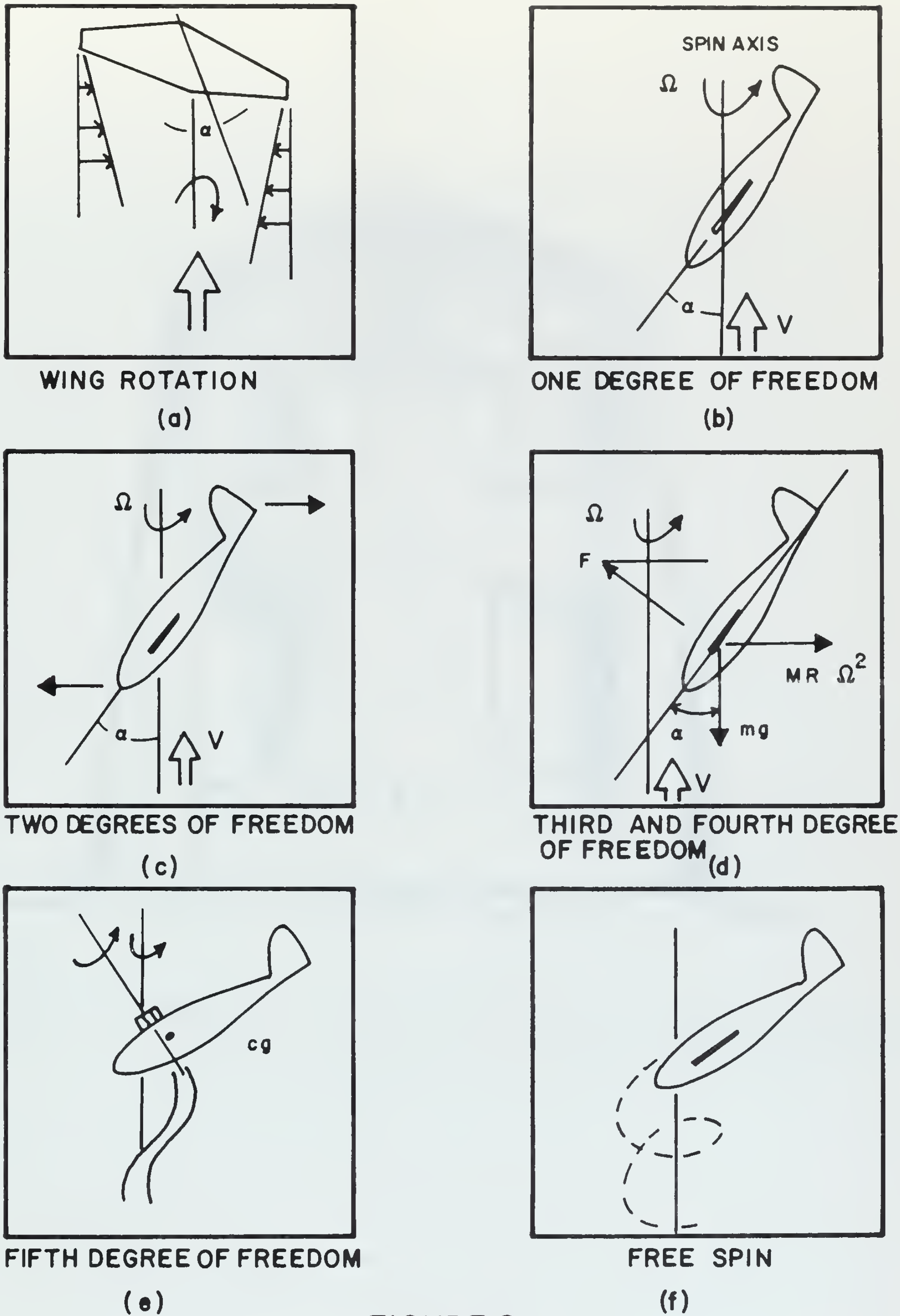

FIGURE 2
DEGREES OF FREEDOM
[REF 50]

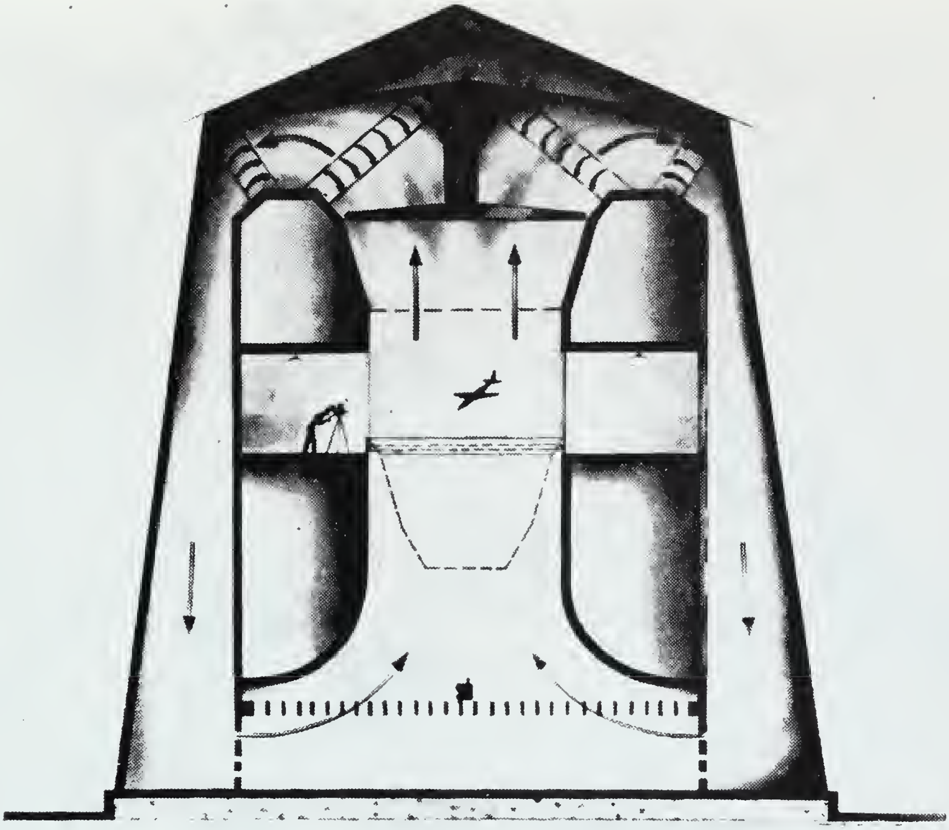

Figure 3. Exterior and Cross-Sectional Views of Langley 20-Foot Free-Spinning Tunnel [Ref. 77].

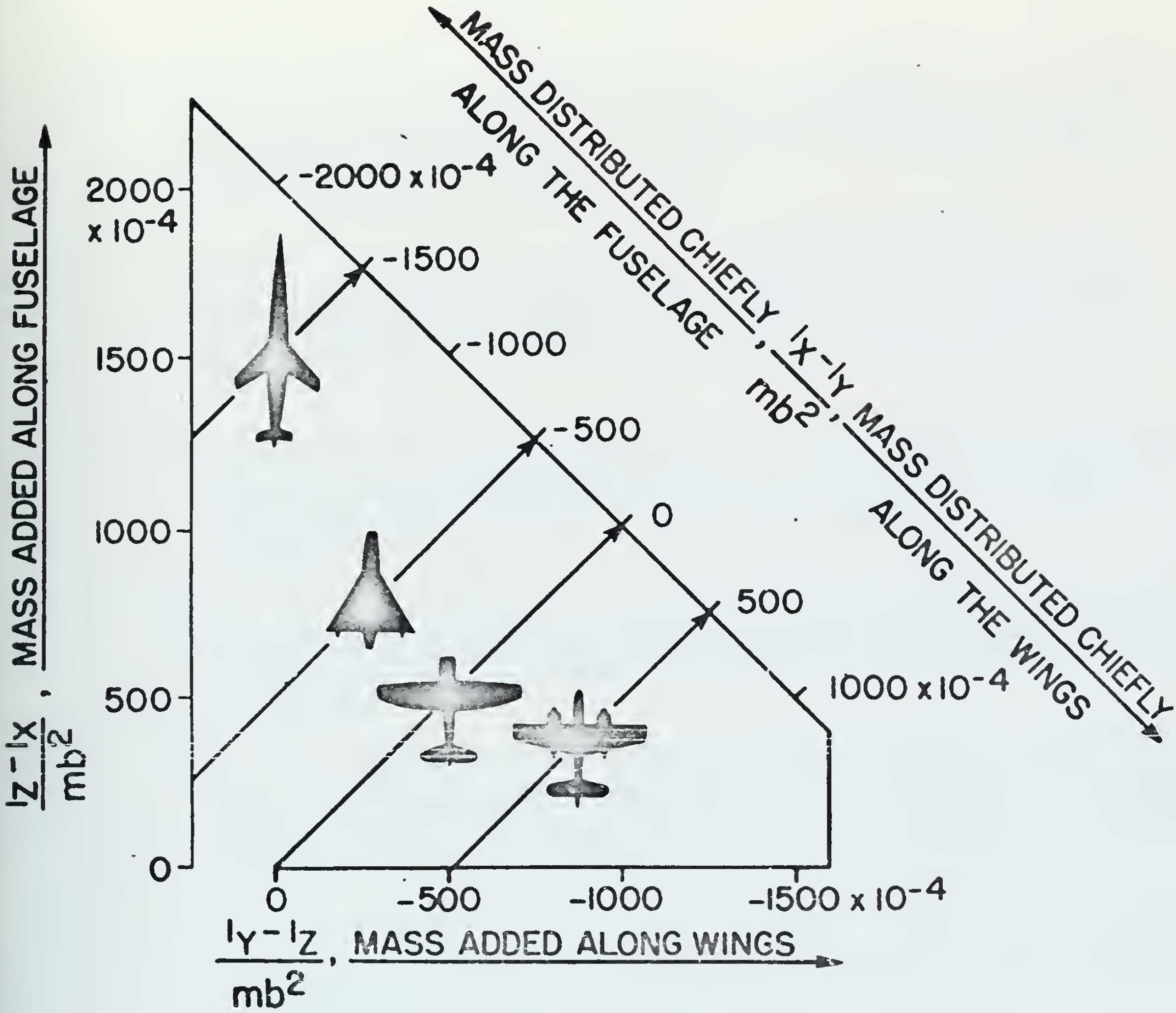

Figure 4. Mass Distribution [Ref. 55].

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13. ABSTRACT

The prediction of aircraft spin characteristics has defied complete scientific analysis. There are, however, a number of research techniques which have been utilized in attempts to understand the mechanism of spin. This paper presents a survey of the literature dealing with spin research and its application to a wide variety of aircraft designs over the period 1916 to 1971

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